R.D. HOSIER

RECEIVER NOISE PERFORMANCE

Noise in any channel of a wideband communications system is composed of noise contributions of several types, such as thermal, intermodulation, echo path distortion, interference and noise from the multiplex equipment. In this section our concern will be the noise contribution of the receiver portion of the communications system. Special interest in this section is devoted to the inherent noise in receiver circuits designated as noise figure and thermal noise.

Recall from noise types that Noise Power (NP) equaled KTB. We calculated this to be -114 dBm per MHz bandwidth. This is the basic noise power at the input of a device due to thermal sources outside of the device.

NOISE FACTOR AND NOISE FIGURE

Consider the ideal amplifier in Figure 1.

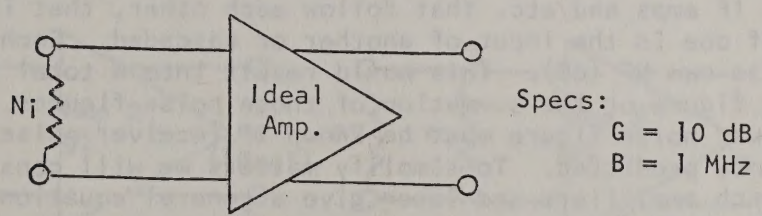


Figure 1 -- Ideal Amplifier

An ideal amplifier is considered noiseless, i.e., it does not generate noise internally. That means the noise out (N_o) equals the noise in (N_i) in dBm plus it's power gain in dB. The resistor at the input of the amplifier represents thermal noise sources external to the amplifier. The noise power input (N_i) was calculated to be -114 dBm per Mhz bandwidth. Since the ideal amplifier doesn't contribute any noise of its own, the noise output is

$$\begin{aligned} N_o \text{ (dBm)} &= N_i \text{ (dBm)} + \text{Gain (dB)} \\ &= -114 \text{ dBm} + 10 \text{ dB} \\ &= -104 \text{ dBm} \end{aligned}$$

Of course, we don't have ideal devices. The components them-

Noise Factor and Noise Figure cont.

selves generate noise of their own, over and above N_i (dBm). When we evaluate a receiver we must also account for this additional noise.

Consider again the amplifier in Figure 1. Only now we realize it isn't ideal. If it were ideal, in our previous example we would have N_o = -104 dBm, but, what if we measured the noise out to be -98 dBm? This difference of 6 dB then represents the additional noise generated by the amplifier called Noise Figure (NF).

To formally define noise figure we must first consider another parameter called noise factor (nf), which is the ratio of the real noise power out to the noise power out of an ideal device, or

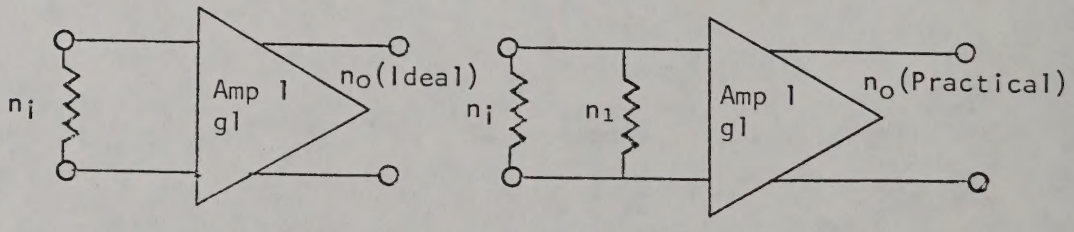
$$nf = \frac{\text{noise out of non-ideal device (watts)}}{\text{noise out of ideal device (watts)}}$$

The noise figure is

$$NF\ (dB) = 10 \log (nf)$$

NOISE FIGURE OF CASCADED DEVICES

In a typical receiver there are several amplifiers such as RF amps, IF amps and etc. that follow each other, that is, the output of one is the input of another or cascaded. Each amplifier has its own NF (dB). This would result into a total receiver noise figure or the summation of those noise figures. The total receiver noise figure must be known if receiver noise performance is to be predicted. To simplify matters we will consider only two such amplifiers and later give a general equation for any number of devices.



Ideal Configuration

Practical Configuration

Figure 2 -- Amplifier 1 in Ideal and Practical Configurations

Noise Figure of Cascaded Devices cont.

Figure 1 shows an ideal amplifier 1 which does not generate any internal noise. The noise output then is

$$n_o \text{ (ideal)} = n_i \, g1$$

where

n_i = thermal noise, KTB in watts
$g1$ = the power gain

Figure 1 also shows the same amplifier but with the noise generated internally represented as n_1. The noise output of this amplifier is

$$n_o \text{ (practical)} = n_i \, g1 + n_1 \, g1$$

The noise factor for amplifier 1 can now be calculated

$$nf_1 = \frac{n_o \text{ (practical)}}{n_o \text{ (ideal)}}$$

$$= \frac{n_i \, g1 + n_1 \, g1}{n_i \, g1}$$

$$nf_1 = 1 + \frac{n_1}{n_i}$$

Next we must consider the second amplifier.

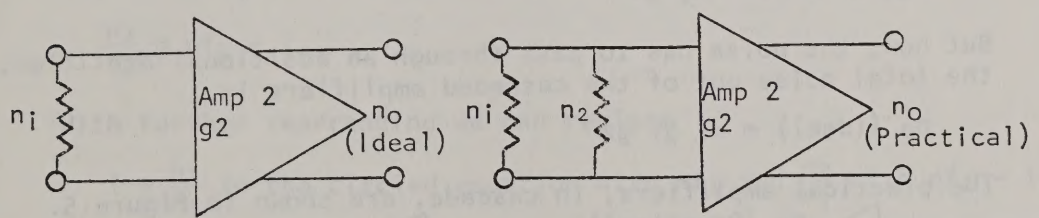


Figure 3 -- Amplifier 2 in Ideal and Practical Configurations

The analysis of this amplifier is the same as for amplifier one, thus

$$n_o \text{ (ideal)} = n_i \, g2$$
$$n_o \text{ (practical)} = n_i \, g2 + n_2 \, g2$$

and

Noise Figure of Cascaded Devices cont.

$$nf_2 = \frac{n_o \text{ (practical)}}{n_o \text{ (ideal)}}$$

$$= \frac{n_i \; g2 + n_2 \; g2}{n_i \; g2}$$

$$nf_2 = 1 + \frac{n_2}{n_i}$$

Now we can consider the effects on noise factor when the two amplifiers are connected cascade. Ideal amplifiers in cascade are shown in Figure 4.

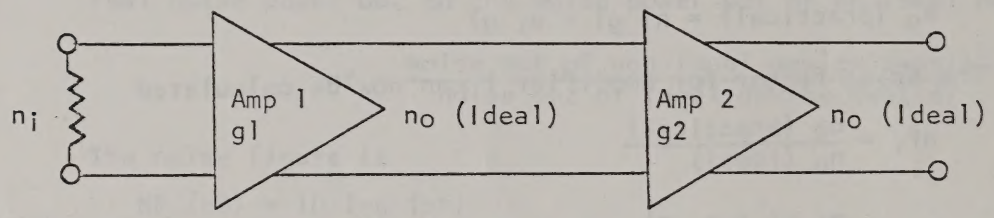


Figure 4 -- Ideal Amplifiers in Cascade

As has been shown previously,

$$n_{o1} \text{ (ideal)} = n_i \; g1$$

But now, the noise has to pass through an additional amplifier. Thus, the total noise out of the cascaded amplifiers is...

$$n_o \text{ (ideal)} = n_i \; g1 \; g2$$

The practical amplifiers, in cascade, are shown in Figure 5.

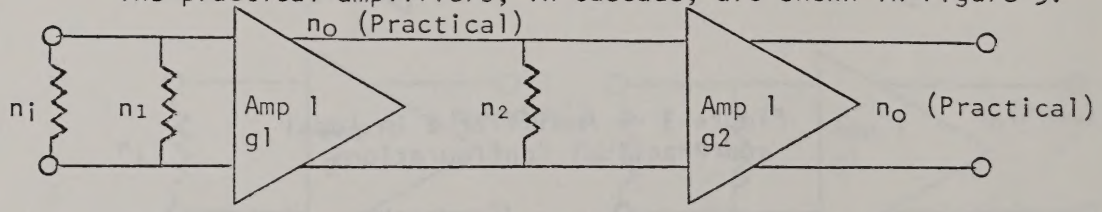


Figure 5 -- Practical Amplifiers in Cascade

The noise power output of the first practical amplifier connected in cascade is

$$n_{o1} \text{ (practical)} = n_i \; g1 + n_1 \; g1$$

The total noise power output of the two practical amplifiers connected in cascade is

Noise Figure of Cascaded Devices cont.

$$n_o \text{ (practical)} = g2\ [n_{o1} \text{ (practical)} + n_2]$$
$$= g2\ [n_i\ g1 + n_1\ g1 + n_2]$$

thus,

$$n_o \text{ (practical)} = n_i\ g1\ g2 + n_1\ g1\ g2 + n_2\ g2$$

With this information we can now find the overall noise factor of the cascaded amplifiers.

$$nf \text{ (overall)} = \frac{n_o \text{ (practical)}}{n_o \text{ (ideal)}}$$
$$= \frac{n_i\ g1\ g2 + n_1\ g1\ g2 + n_2\ g2}{n_i\ g1\ g2}$$

thus,

$$nf \text{ (overall)} = 1 + \frac{n_1}{n_i} + \frac{n_2}{n_i\ g1}$$

But, we found that

$$nf_1 = 1 + \frac{n_1}{n_i}$$

and

$$nf_2 = 1 + \frac{n_2}{n_i}$$

The later equation can be rearranged to give...

$$\frac{n_2}{n_i} = nf_2 - 1$$

With further rearranging we can replace

$1 + \frac{n_1}{n_i}$ in the circled equation with nf_1 and $\frac{n_2}{n_i}$ with $nf_2 - 1$

to obtain

$$nf \text{ (overall)} = nf_1 + \frac{nf_2 - 1}{g1}$$

The above expression if for two stages in cascade. The equation can be expanded to get a general expression for finding overall noise factor of many cascaded devices, where "x" represents the total number of devices in cascade:

$$nf \text{ (overall)} = nf_1 + \frac{nf_2 - 1}{g1} + \cdots \frac{nf_x - 1}{g1\ g2 \cdots g_x - 1}$$

Overall Noise Figure can be found by converting nf (overall) to dB, i.e.,

NF (dB) = 10 log (nf)

Noise Figure of Cascaded Devices cont.

In summary, the following points concerning noise figure should be remembered:

1. To find the overall noise figure of cascaded devices, you must first convert the NF (dB) to noise factor and G (dB) to power gain for each device.
2. If the gain of the first stage of a system is high (20 dB or more), the overall noise figure will be close to the noise figure of the first stage.
3. If no RF amplifier is used as the first stage, then the overall noise figure for the receiver is the noise figure for the mixer.

IF BANDWIDTH

As we discussed earlier, the IF bandwidth is the narrowest of all RF bandwidths. Hence, the IF stages provides the ultimate in selectivity for the receiver. The IF amplifiers gives the greatest amplification within the receiver and it is important that all spurios signals and interference be sharply rejected. IF bandwidth is normally measured at the 3 dB points. The IF bandwidth and frequency response are very important factors in our consideration of receiver noise performance.

Recall noise power equaled KTB. In a previous discussion, we found K and T to be constants. The bandwidth of a device then becomes critical because the thermal noise power increases as the bandwidth of the IF increases. In order to limit the thermal noise, the IF bandwidth should be as narrow as possible.

Unfortunately, having too narrow a bandwidth can create other noise problems. Not all of the significant sidebands would be processed by the IF when its bandwidth is too narrow which results in intermodulation distortion.

As is often the case, the increase in noise that results from sideband suppression is usually much greater than the thernal noise which results by making the IF bandwidth wide enough to pass all significant sidebands. Therefore, the intermodulation noise consideration establishes the bandwidth of the IF stages.

The flatness of the IF stages is also important. Variations in IF response may introduce phase distortions which results in a rise in noise. A non-linear response can affect the limiting action in the receiver which could result in noise caused by amplitude variations of the incoming signal. One final consideration is the symmetry of the response, i.e., equal bandwidth on either side of center frequency. If not symmetrical, intermodulation distortion

IF Bandwidth cont.

will increase as a result of sideband suppression.

RECEIVER NOISE THRESHOLD

Noise threshold is defined as the received signal level (RSL) at which the RMS signal is equal to the RMS noise at the input to the demodulator.

So, then, how much total noise is there at the input of the demodulator? We know from our discussion on thermal noise that the amount of thermal noise contribution is -114 dBm/MHz bandwidth (calculated from noise power = KTB). This is the level of noise due to the antenna and transmission lines at the receiver input.

We also know that the IF bandwidth will limit said amount of thermal noise. So, the -114 dBm/MHz bandwidth value has to be adjusted by the IF bandwidth. This is done using a bandwidth ratio formula which results in a dB value that can be added directly to the -114 dBm/MHz value, hence...

$$\text{Bandwidth of the IF in dB} = 10 \log \frac{BW}{1 \text{ MHz}}$$

Where

BW is the actual bandwidth of the IF stages in MHz.

This value in dB is then added to -114 dBm/MHz to adjust the amount of thermal noise actually allowed to reach the demodulator by the IF stages.

One more consideration to make is the noise added by the receiver components themselves. Earlier we called this the noise figure. Our earlier discussion started with noise factor which we converted to noise figure of cascaded devices in dB units. Since we have noise figure in dB units, it can now be added to the -114 dB/MHz bandwidth along with the value obtained using the bandwidth ratio formula to give the total RMS value of the thermal noise contribution at the input of the demodulator. This, then, is the value of thermal noise that the received signal level must overcome. Said noise value is the noise threshold (TH_n) value, expressed mathematically as...

$$TH_n = -114 \text{ dBm/MHz} + NF \text{ (dB)} + 10 \log \frac{\text{IF BW (MHz)}}{1 \text{ MHz}}$$

reduced further

$$TH_n = -114 \text{ dBm/MHz} + NF \text{ (dB)} + 10 \log BW_{IF}$$

Receiver Noise Threshold cont.

Where TH_n = noise threshold in dBm
BW_{IF} = IF bandwidth in MHz
NF = receiver noise figure in dB

RECEIVER FM THRESHOLD

Recall our definition of receiver noise threshold. The value obtained in the formula for TH_n is the RMS value for both the received signal level (RSL) and noise at the input of the demodulator.

Recall, also, that the peak factor for noise is 13 dB and that of a sine wave is 3 dB. An unmodulated carrier can represent the receive signal to the demodulator input. If both were at the same RMS value at the input of the demodulator, their peaks differ by 10 dB, such is the case at TH_n. At this point the demodulator is responding to the noise peaks. Since the value of noise at the input of the demodulator is constant, the noise out of the receiver is at its worst (noise saturated). The signal must overcome this amount of noise. To do so means the carrier power must be increased until the signal peaks exceed the noise peaks 99.999% of the time. To accomplish this the carrier level must be raised by a minimum of 10 dB. This point is defined as receiver FM threshold (TH_{FM}), or

$$TH_{FM} = TH_n + 10 \text{ dB}$$

or

$$TH_{FM} = -104 \text{ dBm/MHz} + NF \text{ (dB)} + \log BW_{IF}$$

This is the formula used to calculate the <u>minimum</u> signal level that can be demodulated by the receiver.

What we have discussed thus far is a relationship of carrier power to noise power (C/N) at the input of the demodulator which results in a certain signal to noise value at the output of the receiver. Once the carrier value is raised in level enough so that the demodulator responds to carrier peaks instead of the noise peaks (TH_{FM}) the receiver output S/N ratio has improved to minimum usuable value, still not good enough. By increasing the carrier level more, the carrier peaks move further away from the noise peaks so C/N increases which results in an improved receiver output S/N ratio. Since the noise level input to the demodulator remains constant, increasing the carrier level, increases the output S/N ratio proportionally, one dB improvement in S/N out for a one dB improvement of C/N input to the demodulator. This is a linear relationship for values above TH_{FM}.

FM S/N IMPROVEMENT

Derivation of S/N improvement is beyond the scope of this course but can be found in most texts on communications systems. As a factor it is given as...

$$s/n_{Imp} = \left(\frac{\beta}{2b}\right)\left(\frac{\Delta f}{fb}\right)^2$$

Where

s/n_{Imp} = FM s/n improvement factor
β = IF bandwidth in Hz
b = Channel bandwidth in Hz
Δf = Per channel peak deviation in kHz
fb = Center frequency of a voice channel in the baseband in kHz

Put in a more suitable form for this course we have...

$$S/N\ (dB) = 139 + RSL - NF + 20 \log \frac{\Delta f_{rms}}{fb} + P_e$$

Where

S/N = Signal-To-Noise in dB
RSL = C (dBm) = received carrier power in dBm
NF = Total receiver noise figure in dB
Δf_{rms} = Per channel RMS deviation in kHz
fb = Test channel center frequency in kHz
P_e = Amount of pre-emphasis in dB

The above equation describes the S/N improvement to be had at the output of an FM receiver for various C/N values in to the demodulator, a linear equation. Note, also that Pe is added. Earlier we learned of the triangular noise output of the demodulator which was countered using pre-emphasis techniques. The formula shows that for each dB of pre-emphasis, the S/N improvement is a dB, as was learned in an earlier discussion.

Thus far, we have learned what thoughts are considered in terms of receiver noise performance. Can noise performance be predicted? If so, can it be measured? How can we use this information? Simply, predictions can be made; measurements can be performed; and the results can be analyzed which lead to improvements to be made to optimize a receiver's performance.

FM RECEIVER QUIETING CURVES

One of the most important tests performed on the receiver portion of a communications system is measurement of slot noise as the signal input to the receiver is varied. A plot of this data is

FM Receiver Quieting Curves cont.

called a receiver quieting curve. The curve can be predicted and would be used against measured data to determine the receiver's performance. A quieting curve is seen in Figure 6.

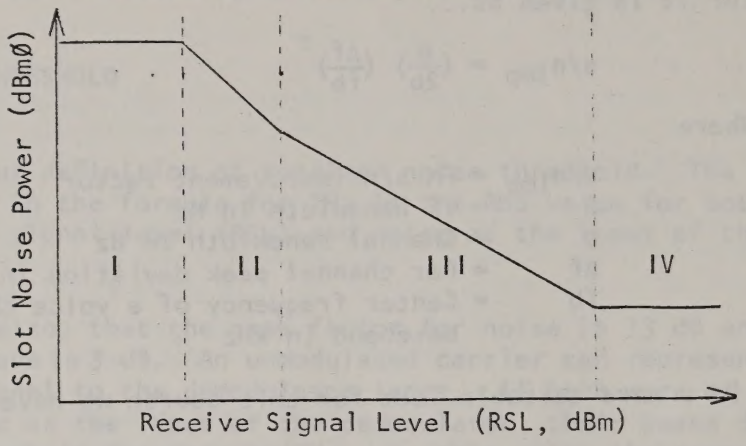


Figure 6 -- Receiver Quieting Curve

The quieting curve in Figure 6 is divided into four regions. Region I is where the RF signal has essentially been lost and the slot noise is dependent on the thermal noise generted within the front end circuits of the reciever, the receiver IF bandwidth, the amount of pre-emphasis, and the amount of receiver limiting.

Region II is a complex function of signal input, the thermal noise generated, the receiver IF response, and the degree of signal limiti Region II is extremely non-linear and is very difficult to define mathematically.

In Region III, the linear region, the slot noise out of the receiver decreases linearly in direct proportion to the signal input level. The noise output in this region is easily defined mathematically as seen in the formula for S/N (dB) = 139 + RSL and etc.

Region IV is the fully quieted region. The slot noise in this region is independent of the received signal level and receiver generated noise. The dominant source of noise in this region is frequency noise which results from random phase variations of various oscillators in the receiver. Frequency noise appearing at the receiver baseband has an essentially flat spectrum in baseband slots above 100 kHz.

The "slot" referred to above is defined as representing a channel baseband slot 3.1 kHz wide. This becomes a test slot that has in it the amount of noise measured at the receiver output (vertical scale) and is compared to RSL at the receiver input (horizontal scale).

FM Receiver Quieting Curves cont.

To get the measured data, an RF signal generator is calibrated in terms of power and receiver center frequency. This, then, becomes the RSL, and is connected to the antenna input port of the receiver. A frequency selective voltmeter (FSV) is used to measure the output noise of the receiver, usually in three baseband test slots; low, middle and high portions of the baseband. The RF generator level is changed a few dBs at a time. For each change, measurements of output noise in the three mentioned slots is made. This information is documented and plotted on graph paper where it is compared to predicted information for analysis. The test hook-up is seen in Figure 7.

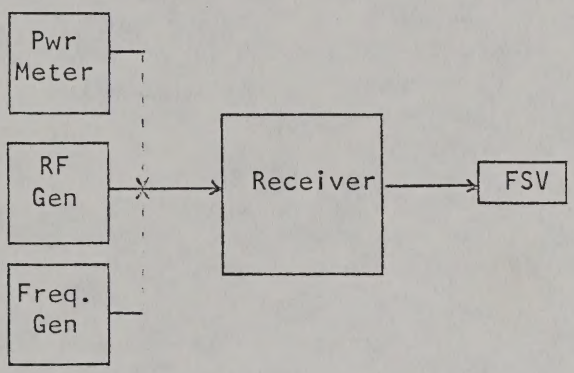


Figure 7 -- Quieting Curve Test Hook-Up

The dashed lines in Figure 7 are not to be connected while performing the test, just to show measurements taken when the RF generator is being calibrated. Impedance values and terms should be observed.

FM QUIETING CURVE PREDICTIONS

We have discussed and have information now to predict three important quieting curve parameters. In particular, we can calculate the following:

1. The RSL at noise threshold (TH_n = -114 dBm/MHz + NF (dB) + 10 log BW_{IF}). This is the vertical line separating Regions I and II.
2. The RSL at FM threshold (TH_{FM} = TH_n + 10 dB). This is the vertical line separating Regions II and III.
3. The S/N at RSLs above FM threshold [S/N (dB) = 139 + RSL - NF + 20 log $\frac{\Delta f_{rms}}{f_b}$ + P_e]. Recall S/N = ØdBmØ - N (dBmØ) because to find points on the vertical scale S/N will have to be converted to dBmØ.
4. To find the line which represents noise in one of the three slots, that runs horizontally from the extreme left side of

FM Quieting Curve Predictions cont.

4. continued

the graph to Regions I and II boundary (found in step 1), use

$$S/N_{SAT} = 9 + P_e$$

the derivation of this formula is beyond the scope of this course. P_e, of course, is the amount for the test slot being calculated for, and S/N will have to be converted to dBmØ because of the vertical scale.

5. In step 3, the linear portion of the curve has been determined and plotted on graph paper. A connection of the line in step 4 is made to the line found in step 4. This becomes the prediction of Region II which we said earlier could not be defined due to the complexity of this extremely non-linear region. This line should not be misconstrued as being definitive, but merely an approximation.
6. It is not necessary to determine where the curve bottoms out (fully quieted) when making predictions. Research has come up with a value for S/N representative of the fully-quieted region which is

$$S/N_{FQ} = S/N_{SAT} + 70 \text{ dB}$$

If measured values are within ±5 dB of this, the receiver is considered to have acceptable performance in this Region (IV).

This concludes our discussion on receiver noise performance. An exercise in predictions will be given in class by your instructor and analysis discussions will clear up any areas that pose a problem to you.